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Genetic optimization of steam multi-turbines system

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HIGHLIGHTS

- Genetic optimization model for a set of five various steam turbines was presented.
- Four various thermodynamic optimization strategies were proposed and discussed.
- Operational parameters (steam pressure, temperature, flow) influence was examined.
- Genetic algorithm generated optimal solutions giving the best estimators values.
- It has been found that similar energy effect can be obtained for various inputs.

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ABSTRACT

Optimization analysis of partially loaded cogeneration, multiple-stages steam turbines system was numerically investigated by using own-developed code (C++). The system can be controlled by following variables: fresh steam temperature, pressure, and flow rates through all stages in steam turbines. Five various strategies, four thermodynamics and one economical, which quantify system operation, were defined and discussed as an optimization functions. Mathematical model of steam turbines calculates steam properties according to the formulation proposed by the International Association for the Properties of Water and Steam. Genetic algorithm GENOCOP was implemented as a solving engine for non−linear problem with handling constrains.

Using formulated methodology, example solution for partially loaded system, composed of five steam turbines (30 input variables) with different characteristics, was obtained for five strategies. The genetic algorithm found multiple solutions (various input parameters sets) giving similar overall results. In real application it allows for appropriate scheduling of machine operation that would affect equable time load of every system compounds. Also based on these results three strategies where chosen as the most complex: the first thermodynamic law energy and exergy efficiency maximization and total equivalent energy minimization. These strategies can be successfully used in optimization of real cogeneration applications.

1. Introduction

More than 80% of world's electricity is generated in systems driven by steam turbines. Despite intensive research in alternative energy resources, it is predicted that this rate will not change significantly during next decades [1]. Cogeneration is one of the possible ways for more efficient primary energy resources utilization. Heat released to surroundings in regular power plants can be used to other processes [2]. Jacobs and Schneider [3] analyzed energy balance in coal-fired, non-reheated, three stages feed water heating power plant having condensing steam turbines and similar size system equipped with backpressure units extracting steam to manufacturing process. This comparison indicated energy losses reduction, related to primary energy, from 65% to 16%. Many industrial plants, where both electricity and heat is used, have own power plants, generating as much electricity as it results from their heat demand (non-utility generation − NUG) [4]. Optimization of such unit is relatively easy in small plants equipped with one turbine. Problem is getting to be complex in larger systems, like chemical, pulp and paper or petroleum refining plants [4,5].

Operation of systems equipped with various steam turbines is obvious, when it is loaded at 100% of the capacity. Situation is more complicated, when manufacturing plant with cogeneration system, is only partially loaded. Improper turbine load can result lower

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Abbreviations

0	surrounding parameters (index)
A, B	regression parameters
A, B, C, D	strategy indicator (index)
ACT	actual parameters (index)
CALC	calculated parameters (index)
DEM	demand (index)
DST	destruction
EL	electricity power [kW]
ETG	electricity turbo–generator
EX	exergy [GJ/h]
FIT	fitness function for optimization
FUEL	parameters related to fuel (index)
H	enthalpy [kJ/kg]
i, j, n, m	iteration integer parameters
IN	inlet parameters (index)
IPS	intermediate pressure system
is	isentropic process (index)
M	steam mass flow rate [kg/h]
MIN, MAX	minimum/maximum values (index)
OUT	outlet parameters (index)
P	pressure [MPa]
PRC	process
REQ	required parameters (index)
Q	heat, chemical energy [GJ/h]
S	entropy [kJ/kg K]
ST	stage of turbine
T	temperature [°C]
W	electricity power [kW]
WST	waste
x	steam quality
X	overall parameter
ΔX	difference value of the parameter X
η	efficiency

overall system efficiency. Previously many steam turbines optimization were conducted [6–8] using also genetic algorithms [9,10]. However those researches were related to just one turbine optimization. Genetic algorithms allow solving more complex systems, for example multi-turbine power plant optimization [12].

In this study methodology for quantitative estimation of steam multi-turbines system, supplying process heating in partially loaded production has been proposed. For this purpose five various strategies have been formulated. For of them are related to the first thermodynamic low optimization: extracted energy balancing, fuel usage minimization and energy/exergy efficiency maximization. The fifth strategy considers total energy effect (electricity and heat) including economical aspect (ratio of electricity/fuel cost).

Genetic algorithm GENOCOP I [11] has been used as an optimization tool. It allows to optimize problems with constrains formulated by inequalities. Some of parameters discussed in the paper were limited constantly by its minimum/maximum range (pressure, temperature, flow rate in the first stage). However, steam flow rates in lower pressure stages were limited by actual flow conditions in previous stage, what complicates the solution.

All of presented results were obtained by own–developed numerical code, programmed in C++, which firstly has been verified in strategy with known solution.

2. Problem formulation

2.1. General process description

The object for optimization has been presented in Fig. 1. The system is equipped with #n steam turbo-generators with #m pressure stages and extraction possibility to intermediate/low pressure steam pipelines. Steam streams, extracted from turbines, mix at required pressure. Finally, steam at conditions IPS #1 – IPS #m is directed to manufacturing process heating PRC #1 – PRC #m-1. Excess steam is rejected to surrounding (WST #1 – WST #m).

The purpose of proposed research is to present a methodology of determination the most optimal turbines operation conditions, when the factory is partially loaded. Original system design was predicted to provide process steam from all of turbines to the manufacturing processes, working at full capacity.

In Fig. 2 possible energy dependencies that can occur in a steam turbines system have been presented.

In the steam system, only parameters of fresh steam (temperature, pressure) and flow rate at the turbines' stages (by its extractions) can be controlled. These three parameters depend on heat requirements and turbines characteristics. They have influence into steam thermodynamic parameters at extraction nodes and simultaneously into fuel consumption, heat production, electricity generation and exergy destruction. It allows combining them in a target function for optimization strategies. Parameters defined as target functions are also interrelated together: higher electricity generation affects higher heat production and fuel consumption, lower exergy destruction causes higher electricity generation and lower heat extraction, etc. Such multi-stage interdependences in connection with mathematical formulation of thermodynamic processes are the subject of optimization methodology presented in the paper.

2.1.1. Mathematical model

For optimization purposes, relations defined qualitatively in Fig. 2 allow to build quantitative model. The model formulation presented in Table 1, indicates calculated parameters, its mathematical form and computation order. The table has three sections. The first section includes control parameters of steam turbines system. Values of flow rate (1) and thermodynamic properties (2), (3) (temperature, pressure) are randomly selected from the range, limited by turbines manufacturer's specification. The second section shows processing of input parameters, to obtain required flow and thermodynamic properties in intermediate nodes. In the first order, based on the mass balance, steam flow rates in extrusion nodes (4) are calculated. It is followed by determination of inlet enthalpy and entropy (5). Isentropic turbines efficiency ($\eta^{ST}_{\#i,\#j}$), used to calculate real outlet parameters from the turbines stage (6) depends on load conditions. These outlet conditions become inlet parameters for the next stage. After that sequence (6) is repeated up to the last extraction node. All steam parameters have been calculated by own developed numerical program (C++), based on Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam [13]. The code was verified with steam tables [14], by comparison of the energy balance for a sample turbine. Final error of this comparison was not higher than ±0.1%.

When flow and thermodynamic parameters are known in all nodes, final assessment calculations, assigned as target functions in the Fig. 2 can be done. Fuel consumption (7) expresses energy that should be provided to water, being in saturation conditions at minimum outlet pressure from turbines, to generate fresh steam at inlet state (2), (3). Generated electricity (8) is a power that can be extracted from turbines under given thermodynamic and flow

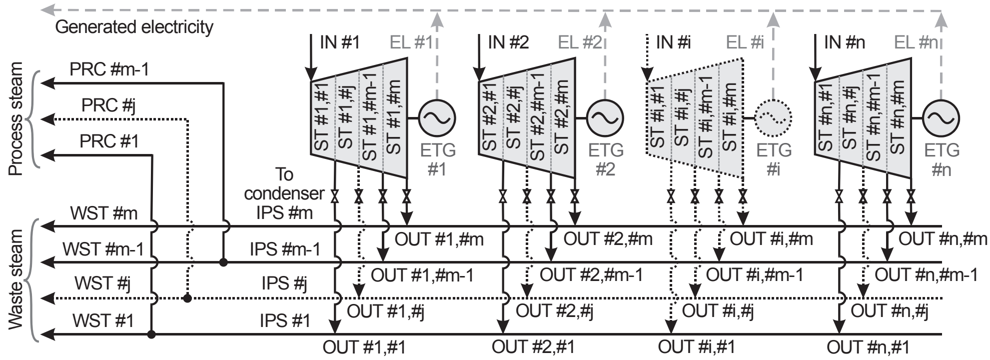

Fig. 1. General layout of steam turbines system (2 columns).

conditions. It has been assumed that efficiency of electricity generators does not depend on its load and as a constant value was neglected in further calculations. Process heat released from turbines (9) was calculated as an equivalent of excess energy, related to saturated water at given outlet pressure. Exergy balance (10) is understood as a maximum work that can be obtained from proposed system, being in specified surrounding conditions [15].

2.1.2. Turbine characteristics

Peterson and Mann [16] provided typical isentropic efficiencies for wide range of full loaded steam turbines. Based on those data Mavromatis and Kokossis [17] proposed equation for the isentropic turbine efficiency (accuracy ±2%), which depends on maximum steam flow rate for the turbine (M_{MAx}), its actual load flow rate (M), enthalpy changes in equivalent isentropic turbine (ΔH_{is}) and two regression parameters (A and B):

$$\eta_{is} = \frac{6}{5}\frac{1}{B}\left(1 - \frac{A}{\Delta H_{is} \cdot M_{MAX}}\right)\left(1 - \frac{1}{6}\frac{M_{MAX}}{M}\right) \tag{11}$$

$$\begin{aligned} A &= -0.928 + 0.00623 \cdot t_{sat}^{IN} \\ B &= 1.12 + 0.00047 \cdot t_{sat}^{IN} \end{aligned} \tag{12}$$

2.2. Optimization algorithm

In the optimization process own developed code (C++) based on the genetic algorithm, GENOCOP (GEnetic algorithm for Numerical Optimization for Constrained Problems) [11] has been implemented. The algorithm allows finding an optimal solution in the task, were a target function limits are given by inequalities. In considered task, only steam parameters are given as equalities (between minimum and maximum values). Steam flow rates are limited not only by capacity of turbines but also by flow conditions in a previous stages.

Diagram of optimization algorithm has been presented in Fig. 3. The process starts from creating *n_ch* (=500) of random chromosomes, which are input data (temperature, pressure, flow rates) to the model, presented in Table 1. In the next step value of these chromosomes is estimating, according to a chosen strategy. In selection algorithm, “stronger” specimens with better estimation rate, have higher probability to be chosen the new population. A genetic operations are the way, how new specimens, built upon existing “parents” are introduced into the population. Chosen *n_repr* (=100) chromosomes are acted by the GENOCOP's six genetic operators (Fig. 3).: three mutations and three crossovers.

In all of mutations just one element in the chain is changed. In crossover operators all elements in chains or their parts are changed. As an effect new chromosomes (one or two) are created, based on one or two parent specimens:

1. **Uniform mutation** – random element in a chromosome is changed randomly within its range
2. **Boundary mutation** – random element in a chromosome gets its minimum or maximum value
3. **Non–uniform mutation** – random element in a chromosome is changed according to randomly chosen formula (Fig. 3); R – random value (0, 1), t – actual age of chromosome, T – age of the oldest chromosome in population, b – power factor (=2.0) [11].
4. **Arithmetic crossover** – two new chromosomes are created, where all elements are changed according to presented formulas (Fig. 3); R – random value in range (0, 1)
5. **Simple crossover** – operator similar to arithmetic crossover, part of chromosome chains remain without changes.
6. **Heurestic crossover** – only one new chromosome is created; R – random value in range (0, 1).

3. Optimization results

3.1. Parameters of the sample system

As an example, system composed of five various steam turbines, connected like in Fig. 1 was optimized. When factory operates at 100% of its capacity, all of five turbines (ETG#1 – ETG#5) work at their nominal parameters (Table 2). Inlet pressure and temperature

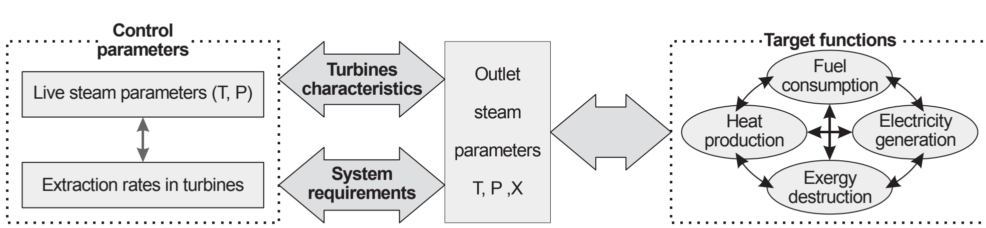

Fig. 2. Possible relationships between control parameters, system characteristics, result parameters and target function (2 columns).

Table 1
Mathematical model of steam turbines operation.

Description	Formulas	Eq. No.
Control parameters of steam turbines		
Steam flow rate at turbine's stages	$M^{ST}_{\#i,\#j} = \mathrm{RAND}\left(0, M^{ST}_{\#i,\#j,\mathrm{MAX}}\right), \quad \text{for} \quad i = 1\ldots n, j = 1\ldots m$	(1)
Inlet steam pressure	$P^{\mathrm{IN}}_{\#i} = RAND\left(P^{IN}_{\#i,\mathrm{MIN}}, P^{\mathrm{IN}}_{\#i,\mathrm{MAX}}\right), \quad \text{for} \quad i = 1\ldots n$	(2)
Inlet steam temperature	$T^{\mathrm{IN}}_{\#i} = RAND\left(T^{\mathrm{IN}}_{\#i,\mathrm{MIN}}, P^{\mathrm{IN}}_{\#i,\mathrm{MAX}}\right), \quad \text{for} \quad i = 1\ldots n$	(3)
Thermodynamic and flow conditions in steam turbines		
Extrusion flow rates	$M^{\mathrm{OUT}}_{\#i,\#j} = M^{ST}_{\#i,\#j} - M^{ST}_{\#i,\#j+1}, \quad \text{for} \quad j = 1\ldots m-1$ $M^{\mathrm{OUT}}_{\#i,\#m} = M^{ST}_{\#i,\#m}$	(4)
Inlet steam enthalpy and entropy	$H^{\mathrm{IN}}_{\#i} = H\left(P^{\mathrm{IN}}_{\#i}, T^{\mathrm{IN}}_{\#i}\right), S^{\mathrm{IN}}_{\#i} = S\left(P^{\mathrm{IN}}_{\#i}, T^{\mathrm{IN}}_{\#i}\right), \quad \text{for} \quad i = 1\ldots n$	(5)
Outlet steam enthalpy and entropy	$H^{\mathrm{OUT}}_{\#i,\#1} = H^{\mathrm{IN}}_{\#i} - \eta^{ST}_{\#i,\#1}\left(H^{\mathrm{IN}}_{\#i} - H\left(P^{\mathrm{IPS}}_{\#1}, S^{\mathrm{IN}}_{\#i}\right)\right)$ $S^{\mathrm{OUT}}_{\#i,\#1} = S\left(P^{\mathrm{IPS}}_{\#1}, H^{\mathrm{OUT}}_{\#i,\#1}\right)$ $H^{\mathrm{OUT}}_{\#i,\#j} = H^{\mathrm{OUT}}_{\#i,\#j-1} - \eta^{ST}_{\#i,\#j}\left(H^{\mathrm{OUT}}_{\#i,\#j-1} - H\left(P^{\mathrm{IPS}}_{\#j}, S^{\mathrm{OUT}}_{\#i,\#j-1}\right)\right)$ $S^{OUT}_{\#i,\#j} = S\left(P^{IPS}_{\#j}, H^{\mathrm{OUT}}_{\#i,\#j}\right), \text{ for } i = 1\ldots n, j = 2\ldots m$	(6)
Target functions		
Fuel consumption	$Q^{FUEL} = \sum_i Q^{\mathrm{FUEL}}_{\#i} = \sum_i M^{ST}_{\#i,\#1}\left(H^{\mathrm{IN}}_{\#i} - H\left(P^{\mathrm{IPS}}_{\#m}, X = 0\right)\right), \quad \text{for} \quad i = 1\ldots n$	(7)
Generated electricity	$W^{EL} = \sum_i EL_{\#i} = \sum_i \left[\begin{array}{c}\left(M^{ST}_{\#i,\#1}\left(H^{\mathrm{IN}}_{\#i} - H^{\mathrm{OUT}}_{\#i,\#1}\right)\right) + \\ + \sum_j \left(M^{ST}_{\#i,\#j}\left(H^{\mathrm{OUT}}_{\#i,\#j} - H^{\mathrm{OUT}}_{\#i,\#j-1}\right)\right)\end{array}\right]$ $\text{for } i = 1\ldots n, \quad j = 2\ldots m$	(8)
Process heat released from turbines	$Q^{\mathrm{CALC}}_{\#j} = \sum_i M^{\mathrm{OUT}}_{\#i,\#j}\left(H^{\mathrm{OUT}}_{\#i,\#j} - H\left(P^{\mathrm{IPS}}_{\#j}, x = 0\right)\right), \quad \text{for} \quad i = 1\ldots n, \quad j = 1\ldots m$	(9)
Exergy balance	$EX^{DST} = \sum_i EX^{\mathrm{IN}}_i - \left(\sum_i EL_{\#i} + \sum_j EX^{\mathrm{IPS}}_j\right)$ $\text{for } i = 1\ldots n, \quad j = 1\ldots m$ $EX = M\cdot[(H - H_0) - T_0(S - S_0)]$	(10)

have been chosen to fit within an operation range of typical turbines [3]. Outlet pressure fits to typical process heating thermal parameters, required in industry (pulp, paper, chemical, etc.)

3.2. Optimization strategies

Optimization calculations have been done for sample factory loads at 50% of its capacity, for four various strategies. The aim of optimization is to find such set of input parameters, which gives the best factors described by each strategy, discussed below. Each strategy has been evolutionary processed 20–50 times and finally 10 the best solutions have been chosen. All results have are presented together in Fig. 4.

3.2.1. Strategy A: energy balancing

The aim of this strategy is to find such input parameters that allow for accurate steam release from turbines extraction, covering heat requirements in manufacturing process heating. The strategy equation for optimization can be formulated as a function of difference between calculated heat transfer and nominal heat, required for process heating:

$$FIT_A = MIN\left(\sum_j \left|Q^{\mathrm{CALC}}_{\#j} - Q^{\mathrm{REQ}}_{\#j}\right|\right), \quad \text{for} \quad j = 1\ldots m-1 \qquad (13)$$

Optimization results are presented at the logarithmic scale (Fig. 4), shows variety of solutions and its accuracy.

This strategy allows also for verification of proposed optimization tool (GENOCOP). The best solution of the strategy equation (13) equals zero, when heat released from turbines (Q^{CALC}) exactly covers with manufacturing requirements (Q^{REQ}). In Table 3 detailed heat release to intermediate pressure systems (IPS) and related errors (14), after 1000 populations have been presented.

Data shown in Table 3 prove that after 1000 populations the fitness of found solution, compared to requirements, is better than 0.00083%. Longer calculations affected higher accuracy, however its

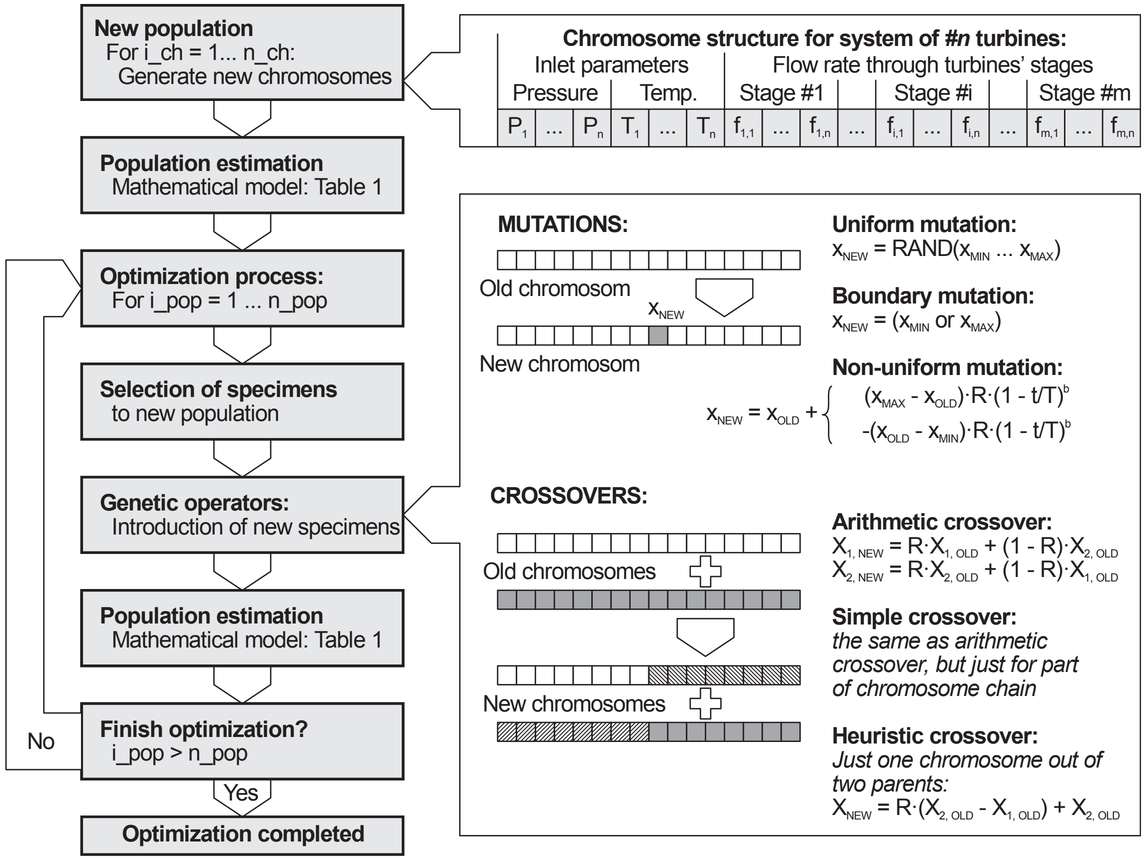

Fig. 3. Evolutionary optimization diagram (2 columns).

magnitude is relatively low, for example, after 5000 and 10000 populations maximum errors are 0.0000143% and 0.0000124% respectively. It positively verifies developed simulation.

3.2.2. *Strategy B: minimization of primary energy usage strategy*

In this strategy, the system is set-up to use minimum primary energy to cover heat demand for the manufacturing process. Electricity generated in a cogeneration plant is second order co-product, as a result of steam flowing through turbines to process heating.

$$FIT_B = MIN\left(Q^{\mathrm{FUEL}}\right) \tag{15}$$

Final results (Fig. 4) after 20 000 optimization steps are distributed in range 1268.26 GJ/h − 1283.81 GJ/h with standard deviation 5.26 GJ/h (0.41%) from average value (1276.77 GJ/h).

3.2.3. *Strategy C: energy efficiency maximization*

In this strategy system is programmed to generate maximum electricity with the lowest fuel consumption, securing heat demand. Some rejected heat, besides manufacturing process heating,

Table 2
Steam turbines nominal parameters for example optimization process.

Turbines characteristics							
Parameters		Unit	ETG#1	ETG#2	ETG#3	ETG#4	ETG#5
Max. inlet steam flow rate		[kg/h]	140 000	180 000	230 000	270 000	350 000
Min. inlet temperature		[°C]	350	350	350	350	350
Max. inlet temperature		[°C]	470	490	500	510	530
Min. inlet pressure		[MPa]	3.0	3.0	3.0	3.0	3.0
Max. inlet pressure		[MPa]	6.0	7.0	7.5	8.0	9.0
Max. stage flow rate	ST#1	[kg/h]	140 000	180 000	230 000	270 000	350 000
	ST#2		98 000	144 000	172 500	243 000	297 500
	ST#3		70 000	36 000	115 000	108 000	210 000
	ST#4		56 000	0	57 500	54 000	140 000
Min. stage flow rate		–	For each stages and turbines it is possible to have no steam flow				

Steam requirements for the manufacturing plant					
Parameters	Unit	IPS#1	IPS#2	IPS#3	IPS#4
Extraction pressure	[MPa]	2.7	1.2	0.25	0.005
Nominal extracted heat	[GJ/h]	469.2663	912.8444	507.3163	–
Total generated electricity	[MW]	208.7448			

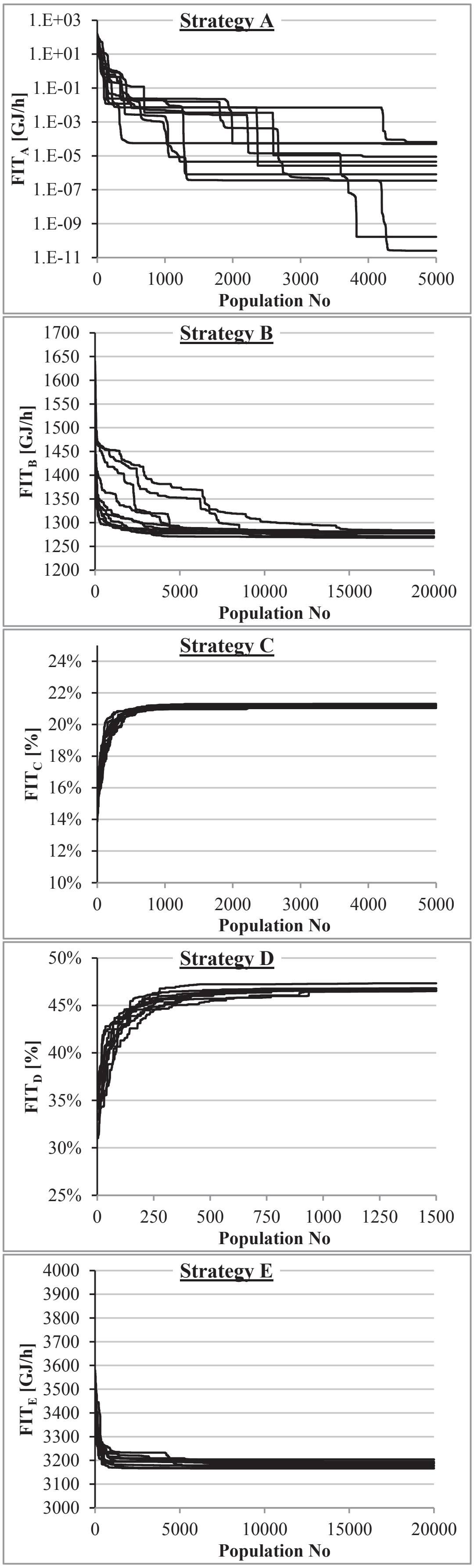

Fig. 4. Genetic optimization progress in proposed strategies (1 column).

is allowed. Fitness function can be presented as the first thermodynamic law energy efficiency, i.e. as a ratio of generated electricity and consumed fuel, with constrains that heat extracted from turbines into intermediate pressure systems must at least cover manufacturing plant needs. Mathematically, the fitness function can be expressed as follows:

$$FIT_C = \mathrm{MAX}\left(\frac{W^{\mathrm{EL}}}{Q^{\mathrm{FUEL}}}\right) \tag{16}$$

Obtained results (Fig. 4) after 5000 populations vary between 21.05%–21.30% with standard deviation 0.09% from average value (21.15%).

3.2.4. Strategy D: exergy efficiency maximization

The system in strategy D is tuned to maximize exergy efficiency and simultaneously to minimize exergy destruction related to inlet steam exergy, that can be achieved from a system being in surrounding at temperature T_0.:

$$FIT_D = \mathrm{MAX}\left(\frac{W^{\mathrm{EL}}}{\sum_i EX_i^{\mathrm{IN}}}\right) \tag{17}$$

Characteristics of this strategy in practical application are similar like in the Strategy C. Obtained results (Fig. 4) after 1500 populations vary between 46.5%–47.30% with standard deviation 0.243% from average value (46.71%).

3.2.5. Strategy E: total equivalent energy minimization

The system in strategy E is tuned to minimize the total energy equivalent used in the manufacturing plant:

$$FIT_E = \mathrm{MIN}\left[Q^{\mathrm{FUEL}} + PCF\cdot\left(0.5\cdot W^{EL}_{\mathrm{DEM}} - W^{\mathrm{CALC}}\right)\right] \tag{18}$$

This equivalent reflects value of total purchased energy by the factory, expressed in energy units. To calculate this value some assumptions have been made. Nominal electricity demand $W^{\mathrm{EL}}_{\mathrm{DEM}}$ for 100% loaded manufacturing plant is twice of nominal power generated in 100% loaded manufacturing plant (Table 2). Electricity power consumption is proportional to manufacturing plant load, i.e.: 50% loaded factory consumed of 50% of nominal power consumption. Price Conversion Factor (PCF) expresses ratio of electricity and fuel price in the same energy units ($GJ_{\mathrm{EL}}/GJ_{\mathrm{HEAT}}$) equals 3.5.

Obtained results (Fig. 4) are distributed in range between 3166.078 GJ/h – 3203.714 GJ/h with standard deviation 13.28 GJ/h (0.4%) from average value (3185.579 GJ/h).

3.3. Strategies comparison

3.3.1. Target functions

All estimators: fuel consumption, generated electricity, energy and exergy efficiencies, exergy destruction, heat released from turbines and equivalent of total energy demand, for results presented in Fig. 4, have been set in Table 4. To make comparison reliable, presented data reflects average value and the standard deviation for 10 obtained results in each strategy. Values optimized in terms of each strategy have been bolded.

In the Strategy A, overall amount of heat released from turbines to manufacturing process (IPS #1, #2 and #3) is the most close to requirements. Fuel consumption is definitely the lowest in the Strategy B. According to expectations, the system efficiency is the highest for the Strategy C and D. Surprisingly Strategy E did not give the lowest values of a total energy demand equivalent. Some better solutions were found within the strategy C, but differences are

Table 3
Verification of genetic algorithm operation after 1000 populations.

Results set	Calculated heat transfer			Error[a]		
	$Q^{CALC}_{IPS\#1}$	$Q^{CALC}_{IPS\#2}$	$Q^{CALC}_{IPS\#3}$	$Err_{\#1}$	$Err_{\#2}$	$Err_{\#3}$
1	234.60435	456.41217	253.65521	0.00307653%	0.00000000%	0.00000001%
2	234.59713	456.43519	253.65536	0.00000038%	0.00504256%	0.00005807%
3	234.59713	456.41223	253.65521	0.00000000%	0.00001240%	0.00000000%
4	234.59713	456.41217	253.65732	0.00000026%	0.00000008%	0.00083160%
5	234.60429	456.41217	253.65521	0.00304962%	0.00000019%	0.00000002%
6	234.59714	456.41248	253.65522	0.00000168%	0.00006835%	0.00000207%
7	234.59714	456.42834	253.65551	0.00000264%	0.00354166%	0.00011719%
8	234.61619	456.41217	253.65521	0.00812561%	0.00000001%	0.00000017%
9	234.59787	456.41497	253.65521	0.00031277%	0.00061253%	0.00000001%
10	234.59851	456.41582	253.65521	0.00058648%	0.00079918%	0.00000044%

[a] $Err_{\#j} = (Q^{CALC}_{\#j} - Q^{REQ}_{\#j})/Q^{REQ}_{\#j}$ (14).

relatively low. Additionally it is clearly presented, that the Strategy E operates at lower fuel consumption and releases less heat from steam turbines than the Strategy C and D.

Also the standard deviation, in most cases, is the lowest for the strategy target functions. The only exceptions are for heat released to IPS#1 (Strategy B < Strategy A) and equivalent of total energy demand (Strategy B < Strategy E). In the first case, the aim of the Strategy A was to find the best solution for total heat released to IPS #1, #2 and #3, so overall results fit the best in this strategy. In the second case slightly lower standard deviation is for equivalent of total energy demand. However it occurs for different conditions, were fuel consumption is the lowest (Strategy B).

3.3.2. *Input parameters*

As it has been shown in Fig. 4 and Table 4, genetic algorithm found some spectrum of possible solutions. Such complex function of 30 variables can have many local extremes. Close to optimal operation, from each strategy point of view can be obtained for different system setup. Since presented results are specific just for example data given in Table 2, detailed analysis of turbines operation has been given up and only general trends were discussed. To clarify comparison, all data have been presented in relative form as a percentage range (0%–100% of parameters specified in Table 2):

$$\text{Reduced Parameter} = \frac{X_{ACT} - X_{MIN}}{X_{MAX} - X_{MIN}} \tag{19}$$

As the first, thermodynamic properties of the fresh steam at turbines' inlet have been compared at the temperature – pressure diagram (Fig. 5). In the strategy A there are no strong dependencies between those two parameters. They get values in all available range. Strategy B is more restricted. Mostly pressure and temperature gets values at its border limits. In the strategy C and D and E, turbines have tendencies to work at the highest possible temperature – pressure level, what is consistent with efficiency increasing methods in the Rankine cycle [14].

Other than extreme points in the last two strategies represents turbine's operation at very low load (flow rate) level and do not have significant influence into overall energy balance.

Steam flow rate through turbines' stages also indicate some deviations. To follow exact relationship between particular steam flow rates, detailed analysis should be conducted. However, it would be related just for this particular example. To make consideration more general, graphs with governing tendencies have been presented (Fig. 6). Strategies in the graphs are organized into 5 groups for turbines (ETG #1 ÷ ETG #5). One group represents all stages (ST#1 ÷ ST#4) load. Singular column in the group reflects average value of 10 calculated flow rates for each strategy, turbine and stage. The error bar is range of one standard deviation for obtained data, based on which the average has been calculated. Real parameters distribution is wider for larger span of the error bars. The lowest steam flow rates occur in the Strategy B. Consequently there is no flow into ST #4 at any turbine in this strategy. Similarity in results of strategies C and D can be explained by their mathematical formulations. Both of them base on the first thermodynamic law analysis with various reference level. The highest steam flow has been noticed for the strategies C and D, what is caused by steam turbines characteristics. Also in these strategies, there is the most intensive steam flow through the last turbines' stage (ST #4). Turbines are designed to work with the best efficiency for higher loads. Steam flow rate in strategy A and E is rated between previously discussed cases. However also in this set important differences can be noticed. In the Strategy A average flow rate occurs around 50% (except ETG #1) with high standard deviation. It means, that obtained singular data are spread within wide range. In the Strategy E mostly two turbines are almost fully loaded while remaining operates at much lower level.

Table 4
Cogeneration system estimators for each strategy.

		Average value/Standard deviation				
		Strategy A	Strategy B	Strategy C	Strategy D	Strategy E
Fuel consumption	GJ/h	1613.47/152.49	1276.81/5.197	2614.26/140.06	2651.42/129.384	2124.14/109.77
Electricity Generation	MW	51.37/13.544	16.4/1.231	153.56/8.118	154.04/7.623	114.08/9.639
Energy Efficiency	%	11.31/2.035	4.62/0.337	**21.15/0.094**	20.91/0.147	19.3/0.638
Exergy Efficiency	%	26.44/4.688	11.5/0.825	47.04/0.197	**46.71/0.243**	42.89/1.497
Exergy Destruction	GJ/h	212.2/45.851	85.42/5.428	524.13/25.89	526.82/23.186	397.77/34.818
Heat to IPS#1	GJ/h	**234.6/0.006**	234.6/0.001	234.96/1.028	234.88/0.362	234.68/0.184
Heat to IPS#2	GJ/h	**456.42/0.008**	456.42/0.009	457.78/2.839	463.56/11.212	456.89/1.274
Heat to IPS#3	GJ/h	**253.66/0.001**	253.86/0.583	392.99/89.002	411.97/74.983	258.87/7.792
Heat to IPS#4	GJ/h	191.03/104.579	0.31/0.912	649.73/8.349	652.22/5.839	468.63/78.328
Equivalent of total energy demand	GJ/h	3464.95/56.408	3568.86/13.306	3178.11/39.016	3209.18/36.678	**3185.41/13.431**

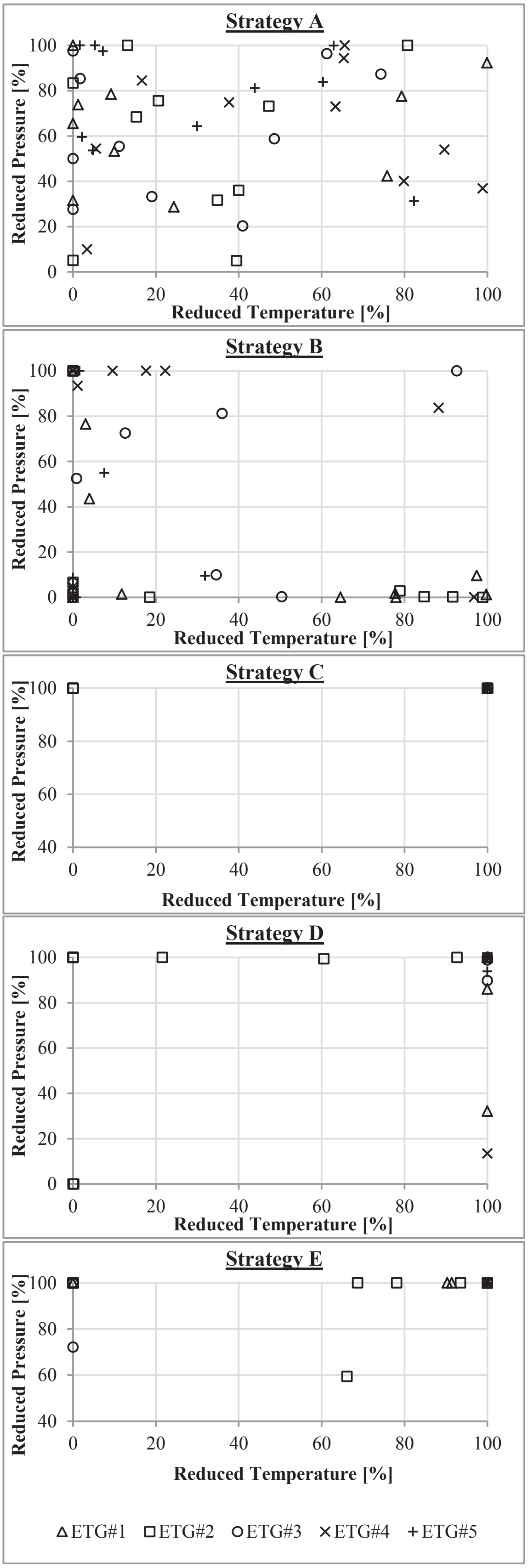

Fig. 5. Relation between fresh steam temperature and pressure at turbines inlet in each strategy (legend for each case under Strategy E) (1 column).

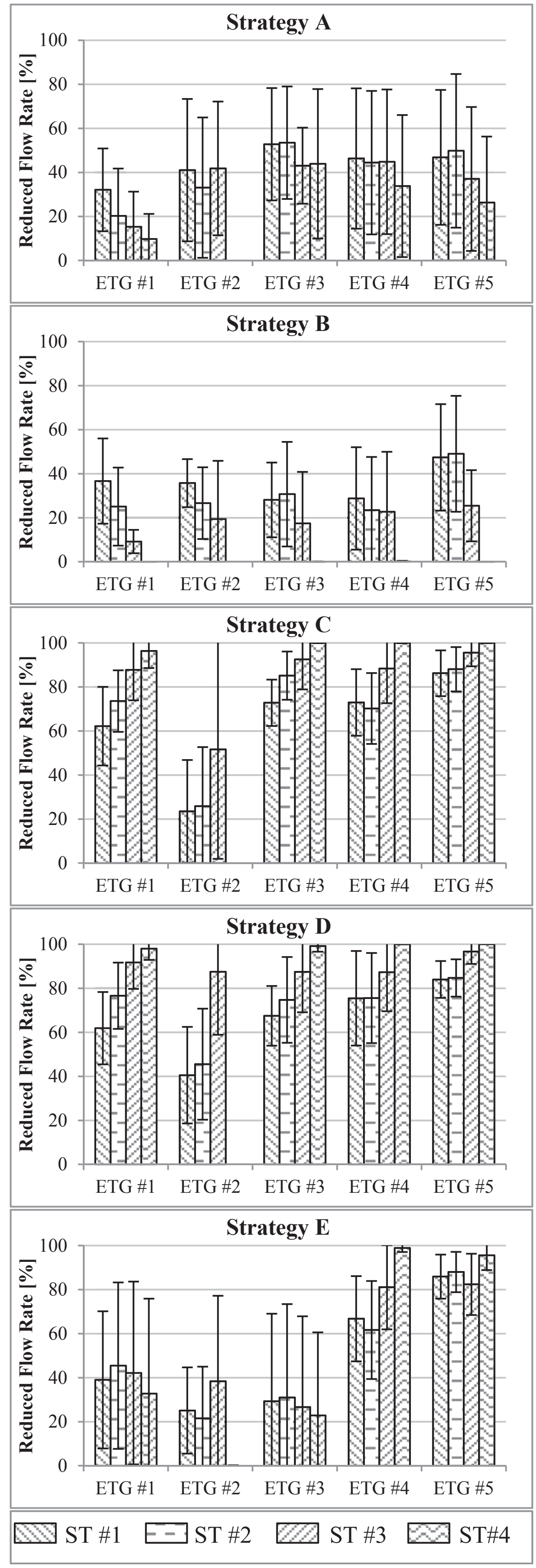

Fig. 6. Steam flow rate through turbines system in each strategy (1 column).

4. Conclusions

In this work, advanced and unique methodology for optimization of partially loaded steam multi-turbines system, working in cogeneration mode has been proposed. Discussed results prove significance of turbines control and appropriate definition of target function into overall energy effect and performance of complex system. As an example, system composed of 5 turbines with various characteristics has been numerically simulated.

Implemented in C++ numerical code has been positively verified in the Strategy 1, where system found parameters for the known solution (Table 4). Additionally final results were compared with calculation done on the basis of available thermodynamic tables for steam, verifying own developed code for steam parameters.

Operational efficiency of a complex steam turbines system can be assessed in many ways. In the paper five various strategies have been discussed: energy balancing, minimization of primary energy usage, the first thermodynamic law energy and exergy efficiency maximization, and finally minimization of energy equivalent related to electricity and fuel prices.

The final solution depends on unknown input parameters, it can be obtained only in complex calculation process. Presented model indicates complexity and variety of turbine set operation. Composition of obtained results depends strongly on chosen strategy. It seems that energy and exergy efficiency maximization Strategies C and D and total equivalent energy minimization Strategy D allows to obtain the most efficient cogeneration plant operation in terms of overall efficiency and energy conversion, however other proposed solutions can be also considered.

The genetic algorithm indicated spectrum of various possible solutions, within one strategy, giving similar final effect. Practical implications of that fact are very important from plant operation point of view. It allows for appropriate load scheduling of particular turbines, to achieve possible equable load time. Also it can be helpful in system maintenance scheduling.

As the next step of this research, proposed methodology can be used in optimization of real cogeneration application, firstly by comparison with actually used techniques and in case of positive verification by implementing obtained results in working system.

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